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TRANSIT MISSION INVESTIGATION FOR SELECTED SURFACE SHIPS

by
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DTRC/SHD-1312-02 Transit Mission Investigation for Selected Surface Ships

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NOMENCLATURE

B	Beam
C_B	Block coefficient
CG	Center of Gravity
FBD	Freeboard
L	Length at the waterline
LT	Long Tons
$\hat{R}$	Bales Seakeeping Rank Factor
R_1	McCreight Seakeeping Rank Factor
$\hat{R}_e$	Walden Extended Seakeeping Rank Factor
T	Draft at midships, (station 10)
T_o	Seaway modal period
T_ϕ	Natural roll period

ABSTRACT

This report applies transit mission criteria to a representative fleet of 16 Naval ships. The Percent Time Operabilities for each ship are presented and limiting motions determined. A sensitivity study of the motion limiting criteria was conducted to indicate the possible benefit of various motion control devices. Limited regression analysis was performed in an attempt to find a correlation between operability estimates and seakeeping rank factors.

ADMINISTRATIVE INFORMATION

This investigation was sponsored by the Chief of Naval Research, Office of Naval Technology, Code ONT21, under the 6.2 Surface Ship Technology Program (ND1A), Program Element 6212N, Northern Latitudes Project RH21S23, Task 3, Ship Motion Control. The work was performed at the David Taylor Research Center during FY1989 under work unit number 1-1506-920.

INTRODUCTION:

Throughout the ages, ships have been required to operate in adverse conditions including strong winds, precipitation, sub-freezing temperatures, and heavy seas. The most influential condition which affects seakeeping quality is the effect of ocean waves. When sea conditions worsen, the operational capability of a ship decreases due to excessive motions. Degradations can range from mild cases of motion sickness to severe restrictions on equipment operability. Manpower intensive evolutions such as Underway Replenishment (UNREP) are particularly sensitive to the effects of ship motions. In extreme cases, a ship's capability can be reduced to a point where survival becomes the primary task of the day.

The seakeeping qualities of a ship can be conveniently predicted using modern strip-theory motion programs, such as the Standard Ship Motion Program (SMP84)[1,2]. Subsequent work by McCreight and Stahl[3] incorporate environmental data with strip theory motion predictions to calculate Percent Time Operability (PTO). PTO calculations depend heavily on the motion limiting criteria which specify the thresholds of unacceptable motion. PTO calculations are a seakeeping measure of merit, allowing comparison of different ships at actual geographic locations for a given mission.

Representative ships from many different naval classes were chosen for the purposes of this study. PTOs for the transit mission at the GIUK gap and a representative North Atlantic ocean point were calculated using the Seakeeping Evaluation Program (SEP)[4].

A sensitivity study of the transit mission ship motion criteria was conducted to determine the relative contribution of each motion limit to total operability.

Regression analysis was performed to determine whether or not a correlation exists between transit mission PTO estimates and the seakeeping rank factors as developed by Bales[5] and McCreight[6].

BACKGROUND

The percent time operabilities (PTOs) estimates for different navy ships can be made using the Seakeeping Evaluation Program (SEP). PTOs are calculated utilizing the transfer functions of the ship of interest to predict motion responses as a function of speed, heading, and the probability of occurrence of significant wave height and modal period combinations. Each ship response is compared to the limiting criteria in each of the seasonal wave spectra which might be encountered in the geographic location of interest. The probabilities of occurrence of the spectra for which none of the motion limits are exceeded are summed to calculate the PTO. The probability of failure is calculated by summing the probabilities of occurrence for each failing wave height-modal period combination.

The criteria sets used to calculate PTOs, consist of motion limits thought to be important to a particular mission, i.e., a response which if exceeded could cause the mission to fail. Typical responses chosen as criteria are: roll, pitch, vertical and lateral acceleration, slamming, deck wetness, and propeller racing. The failure limits of the criteria sets are determined by habitability, operability, and survivability[7].

Habitability is related to the comfort and well-being of a ship's crewmembers. An example of a habitability limit is an 8° significant single amplitude roll limit which is believed to keep crew efficiency above 80%[8], as shown in Fig. 1.

Operability generally involves an interaction between the crew and one or more ship systems. Operability limits are determined by both ship systems capability in rough seas and by the ability of ship's force to operate and maintain the system(s).

Survivability refers to a ship's ability to remain intact in heavy seas. Survivability limits are usually eclipsed by habitability and operability limits which are almost always more conservative.

The accuracy and validity of the PTOs are based on the accuracy of the transfer functions, the motion criteria sets, and the environmental data used in the evaluation. The values for percent time of operability are best used for relative comparisons between hull designs rather than absolute values of operability. Furthermore, the PTOs represent statistical values and should be treated accordingly. This means a PTO of 80%, represents 80% operability during a 20 year period. It does not mean that the ship can operate during any 4 days out of a 5 day period.

ASSESSMENT DETAILS

To facilitate an assessment of seakeeping performance, two northern latitude points were selected for winter season operability comparisons. The first location is the GIUK gap at 61°N; 15°W. The second location is in the North Atlantic Ocean at 56°N; 27°W. Both geographic points represent typical northern latitude regions which experience heavy seas during the winter season. Operability comparisons are displayed in Tables 1 through 3. The performance figures listed represent values for the winter season based on environmental data supplied by the Spectral Ocean Wave Model (SOWM) data base. The SOWM data base contains archived wind data used by the Fleet Numerical Oceanography Center (FNOC) to hindcast wave fields for approximately 1500 locations (grid points) throughout the northern hemisphere. Two severe weather locations were selected to allow subtle differences in hull design to be reflected in differing Percent Time of Operability (PTO) calculations. One must not become greatly concerned about the selection of the grid points. The selection of a geographic point is irrelevant for determining general trends of ship motion criteria on operability values, because the same criteria which limit operability at one location will limit operations at other grid points, just to a different degree.

TRANSIT MISSION CRITERIA SET

The transit mission is defined as simply traversing from point A to point B, without performing any other missions. This implies the limits should be based on crew habitability, hull structure, and propulsion machinery. The habitability criteria are taken

to be roll, pitch, absolute vertical and lateral acceleration at the bridge. Hull structure considerations are accounted for with slamming and deck wetness limits. A propeller racing limit reflects propulsion machinery performance. These limits are suitable for making comparisons, but for use as true operational limits they remain to be validated, especially the habitability criteria.

The transit mission criteria is as follows:

CRITERION	LIMIT
Roll	8° Significant Single Amplitude
Pitch	3° Significant Single Amplitude
Absolute Vertical Accel	0.4 g's Significant Single Amplitude†
Absolute Lateral Accel	0.2 g's Significant Single Amplitude†
Wetnesses at station 0	30 per hour
Slams at station 3	20 per hour
Propeller racing	90 per hour

†The accelerations are calculated at the bridge.

Often the acceleration and propeller racing limits are neglected as unimportant because they rarely limit operability if at all and are position dependent. Furthermore, absolute lateral accelerations do not truly reflect the "transverse" accelerations that affect habitability, i.e. ship referenced accelerations. As a result of this study, general guidelines for when these limits cannot be neglected were developed. Generally, vertical and lateral acceleration limits are included as part of the seakeeping criteria if the T_{ϕ} is less than 15 seconds and/or the displacement is less than 10,000 LT. If the ship has a draft less than 20 feet (6.1 meters), propeller racing should be included as a criterion.

TRANSIT MISSION RESULTS

Roll and pitch are the primary limiting motions in terms of operability for conventional monohulls. This may be because other limits, especially accelerations, are not accurate. Most of the ships examined, regardless of displacement, were limited a larger percent of the time by roll than by pitch. This is especially true in the LST1179 where bilge keels are absent due to unique mission requirements. Roll and pitch become equally important as the ships get shorter in length, especially as L/B is reduced. The only exception was the AO177. The AO177 is predicted to be limited a smaller amount of time due to larger displacement, a fuller midbody, and larger bilge keels in

comparison to most other Navy ships. This reaffirms the idea that efforts devoted toward the reduction of roll motion will yield the the biggest improvement in seakeeping performance for conventional monohulls. This can be done by any number of means, i.e. bilge keels, antiroll fins, antiroll tanks, rudder roll stabilization, and hull form optimization. The benefit of roll motion reduction in terms of improvements in operability can be easily seen using the FFG7 as an example. Without active antiroll fins, the winter North Atlantic PTO is 45. The presence of active control fins raises the PTO to 58, improving transit capability estimates by 13 percentage points. Improving the pitch characteristics is more difficult than roll, because the pitch forces are much larger. Pitch reduction is usually accomplished with antipitch fins or increasing the length. Unfortunately, antipitch fins have problems with induced vibration and re-entry slamming. Small ships can gain the benefits of antipitch fins and large ships can be designed to reduce pitch by ensuring the ship has sufficient length at the waterline.

Other seakeeping factors used in transit operability calculations included slamming, deck wetness, accelerations, and propeller racing. These factors limited operations to a lesser extent than roll or pitch. The percent time limited by slamming was very small. Slamming was a limiting criterion for small to medium sized ships at high speeds. The larger ships were unaffected. Small ships, and oddly the BB62, had deck wetness as a limiting criterion. Deck wetness limited operations near the same speed-heading combinations which were associated with slamming limits. One might expect deck wetness on a small ship. The BB62 results are due to inadequate freeboard. Typical Navy ships have values of FBD/L between 5% and 8%. This value for the BB62 is approximately 4%, indicating inadequate freeboard. Freeboard calculations performed utilizing the methods of Walden and Grundman[9] support this hypothesis.

The vertical and lateral acceleration values are dependent upon the location of interest on the ship. It is obvious that the higher and further a point location is from the center of gravity (CG), the larger the accelerations. Vertical acceleration is a limiting criterion for high speed operations in head to beam seas. Lateral acceleration limits are exceeded in near beam seas conditions. Vertical and lateral accelerations seldom limit operations; usually less than 1% of the time.

Propeller racing was a limiting criterion more often than expected. It tended to be a limiting factor for low T_o, generally high speeds in following seas.

SENSITIVITY STUDY

A transit mission sensitivity study was performed to determine if changes in motion criteria would indicate substantial improvements in operability. By examining the impact of each motion limit on the total PTO calculation, it becomes possible to determine where motion control efforts could be best directed to yield the largest improvements in total operability. Seven hull forms from the representative fleet were chosen: FFG7 with active antiroll fins, TAGO313. DD963, CGN38, CV41, LSD41, and AO177. These ships represent a variety of Navy monohulls in terms of size and mission Winter PTO calculations were made at a geographic location in the GIUK gap in longcrested seas. Longcrested seas were favored over shortcrested seas in the operability comparisons because operability trends would be easier to identify in the longcrested PTOs. The spreading of wave energy in shortcrested seas causes the ship response to be "averaged" over heading. Therefore, minor motion improvements revealed in longcrested PTO calculations might disappear in the shortcrested case.

The sensitivity of the PTOs to the main limiting criteria, roll, pitch, slamming, deck wetness, and propeller emergence, was examined. This study was conducted by individually relaxing one motion limit by 25% while maintaining the original values for the other motion limits. For example, to study roll sensitivity, the roll limit was increased from 8° to 10°, and the other limits kept the same forming a *roll sensitivity* criteria set. The percent time limited by individual criteria was calculated along with the total PTO for each of the sensitivity criteria sets. These results were compared with the original transit mission results for the seven hull forms in Tables 4 and 5.

When a substantial improvement was found in PTO, it was indicative that other motion criteria were not large factors in limiting operability. During these instances, the threshold for one ship motion was exceeded well before the other motion limits. At each speed-heading combination, the limiting wave height lines for each ship motion criterion were not close to one another, as illustrated in Fig. 2. In some cases, however, a relaxation of one criterion caused little change in total PTO because of an increase in percent time limited by other criteria. This usually occurred when the limiting wave height lines for the individual motions were found to be close together, see Fig. 3.

Limiting wave heights for individual criterion are usually close together when the criterion are related, e.g., pitch, slamming, and deck wetness, or roll and lateral accel-

eration; or when the limiting criterion switch from one to another. The largest gains in total operability can be obtained by making improvements in motion reduction involving the most restrictive limiting criterion.

From the seven ships considered, the reduction of roll motion would result in the greatest improvement in PTO for four of them, DD963, CGN38, CV41, and LSD41. The reduction of roll (simulated by relaxing the roll limit) leads to a slight increase in the percent time the ship is limited by pitch, but results in an overall increase in PTO because the pitch limitation occurs at a higher significant wave height. The pitch limitation increases along the boundary between being pitch or roll limited. The average increase was 4.9% for the four ships.

The relaxation of the pitch limit also provided a large increase in overall PTO, especially for the TAGOS13, AO177, and FFG7 with active antiroll fins. These ships derive greater benefits from pitch relaxation for different reasons. The TAGOS13 is a short ship with poor pitch performance. Any improvement in the ship motion limits is extremely beneficial. The AO177 and the fin stabilized FFG7 have already achieved most of the useful roll improvement. Therefore, pitch motion reduction is the next logical place to make operability gains. When the pitch limit is relaxed, the many associated motions become limiting criteria. This is different from improving the roll limit where typically just the percent time limited due to pitch increases. With pitch relaxation, the percent time limited by roll, slamming, deck wetness, vertical acceleration, and propeller racing may increase with an improvement in total operability. Vertical acceleration and propeller racing are not limiting criteria when the pitch limit is relaxed, if they were not identified as problems in the original transit mission operability estimates. Propeller racing is a limiting criterion at higher speeds in following seas. The average PTO increase of the three ships due to pitch relaxation was approximately 4%.

The limits caused by slamming, deck wetness, accelerations, and propeller racing appeared to have a very minor impact on total operability. Relaxing their limits did not tend to increase PTO significantly. Lateral acceleration was a limiting criterion at such large wave heights that the percent time limited by this motion appeared to be negligible.

REGRESSION

The early work of Bales[5], as well as the follow-on works of Walden[10] and McCreight[6], to estimate seakeeping performance based on a relatively simple equation with variables typically available in the early design stage were examined. After accumulating much data for the representative ships, an effort was made to determine whether or not a correlation could be found between the existing seakeeping ranking methods and the transit mission PTOs. The PTOs were compared for the open ocean North Atlantic location during the winter season in longcrested seas. All speed-heading combinations were weighted equally.

The seakeeping ranking methods considered were the Bales, $\hat{R}$; Walden, $\hat{R}_e$; and McCreight, R_1 ranks. The seakeeping ranks are calculated by averaging the RMS response of eight (8) ship motion related quantities for longcrested head seas. The 8 quantities were calculated for 5 speeds and 5 modal periods. The Bales regression equation is only valid for destroyer-type hulls having a displacement of 4300 tonnes, while the Walden equation is valid for displacements from 3000 to 9000 tonnes. The McCreight equation is valid for all displacements. The seakeeping rank is to be "a robust, criteria-free index, independent of specific details and operational areas."[9]

There are many differences between these seakeeping ranking methods and the PTOs; the PTOs consider all headings, use motion limiting criteria, and environmental data from specific geographic locations. The seakeeping rank factors were derived from head seas calculations. However, it is exactly because of these differences that we wish to make a comparison. If a good correlation exists between the seakeeping ranks and the PTO calculations, then overall performance can be assessed early in the design process without worry that the highest ranked ship will have poor seakeeping performance at other speeds and headings. It then becomes possible to determine when a head seas ranking method can be used to judge overall operability. The transit mission criteria is general enough not to overly penalize non-standard ships and represents half of the seakeeping related quantities used by the ranking methods. As to specific geographic locations, this distinction is relatively unimportant as the general trends should be similar regardless of where the PTOs are calculated. Regression equations developed at one point will not necessarily be valid at another. The level of correlation may change at different geographic locations, because of differing modal periods present which may

excite more roll response severely penalizing the head seas assumption.

The correlation between $\hat{R}$ and the PTOs was rather poor, i.e., a high $\hat{R}$ did not necessarily indicate a high PTO, neither did a low $\hat{R}$ indicate a low PTO. This scatter is expected as only two of the ships are destroyers and most are much larger than 4300 tonnes. The scatter simply becomes a measure of $\hat{R}$'s robustness, as shown in Fig. 4.

The extension of $\hat{R}$ to displacements other than 4300 tonnes was done by Walden[10]. The extended factor, $\hat{R}_e$, shows a much better correlation with the PTOs, see Fig. 5. This simple change shows the importance of choosing pertinent regression parameters and underscores the serious limitation of the displacement restriction on $\hat{R}$.

As illustrated in Fig. 6, the McCreight seakeeping rank, R_1, has a strong correlation with PTO, .i.e., generally a large R_1 indicates a large PTO. This trend is apparent even though none of the ships compared were completely within all the parameter ranges. Therefore, the McCreight seakeeping rank can be considered very robust.

A regression of the PTOs using the same variables as Bales and McCreight, except for the cut up ratio, was done. This is in effect finding new coefficients, based on the PTOs, for the $\hat{R}$ and R_1 equations. The extended factor, $\hat{R}_e$, variables were not regressed with the PTOs, but should follow the same trends as the McCreight factor, R_1. As illustrated in Fig. 7, the regressed PTOs were plotted on the same graph as the SEP calculated PTOs. This indicates for which ships those variables and hence $\hat{R}$ and R_1, provide a good prediction of the PTOs. Ships with either large roll motion, small displacements, or very large displacements showed the largest differences. The Bales seakeeping rank, $\hat{R}$, is a valid indicator of performance if the ship's displacement is close to 4300 tonnes and has small roll motion. The McCreight seakeeping rank, R_1, shows some difference probably due to only using head seas response.

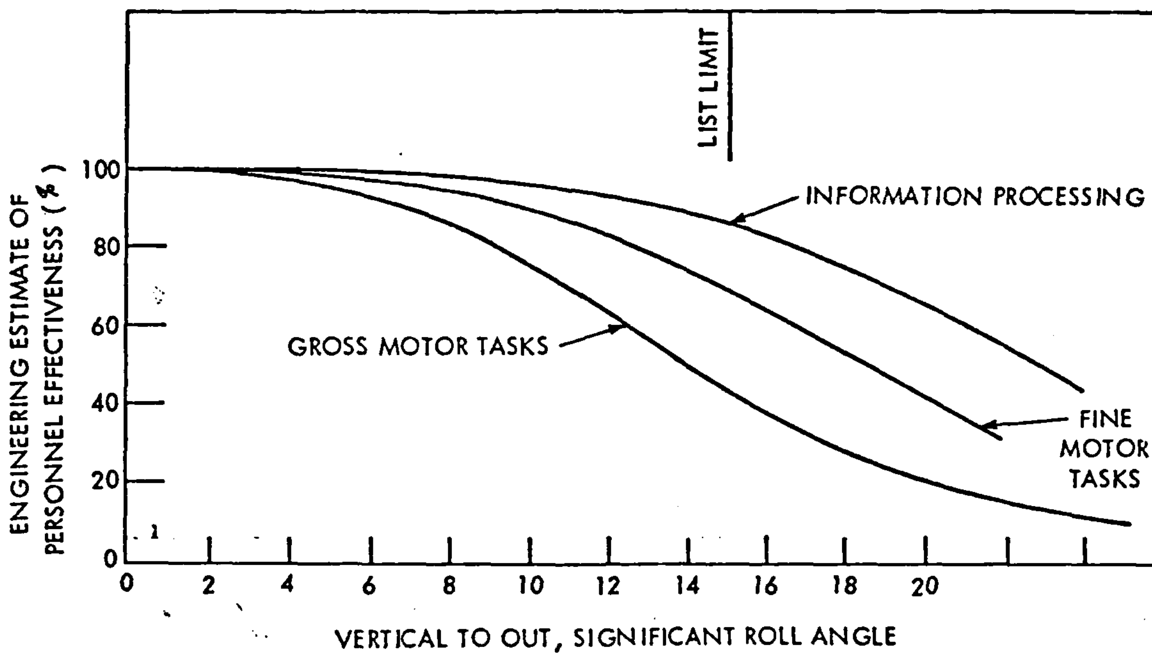
As with the Bales variables, an equation for PTO using the McCreight variables was found. The PTOs from this equation are closer to the SEP calculated PTOs, than the Bales PTOs. This reinforces the statement by Walden and Grundman[9] that the Bales variables may not be the best ones. As to regression results, there seems to be no universal trend as whether the regressed PTOs are larger and smaller than the SEP calculated PTOs. The McCreight seakeeping rank, R_1, seems less constrained by the head seas assumption than Bales.

CONCLUSIONS

The transit mission criteria set was applied to 16 Navy ships, representative of the fleet. Examination of the PTOs and time limited by each criterion identify which ships are the best seakeepers and which criterion is most damaging to PTOs. Displacement plays a large role in seakeeping performance, the two smallest ships having the worst PTOs. Ships with double the displacement have much better PTOs. The ships with the highest PTOs had the largest displacements; however, to attain the high PTOs, the displacements are very large, and it becomes harder and harder to reap the benefits of size as size increases. For example, if doubling the displacement reduced the motions by half, the increase in displacement would quickly become prohibitive and the reduction in motions negligible. Length, beam, draft, and C_B also showed good correlation with the PTOs.

Of the eight criteria thought to limit the transit mission, the two that reduced the PTO the most were roll and pitch. The reduction of roll, more than any other motion would improve seakeeping the most.

Regression analysis showed the relationship between the seakeeping ranking factors and criteria, and the PTOs. The extended Bales and McCreight seakeeping factors showed good correlation with PTOs; the original Bales seakeeping factor did not. Both $\hat{R}_e$ and R_1 can be used to predict total seakeeping performance even though they are derived strictly from head seas performance ranking. Furthermore, $\hat{R}_e$ and R_1 appeared to be good indicators of seakeeping performance for conventional monohulls outside the range of regression parameters used in the initial studies.



NOTE:
1. Estimates are for a medium size ship after 8 hour period and with a reasonably periodic roll.
2. Effectiveness parameter is a function of the time of task performance that is 50 percent effectiveness means a task will take twice as long to perform with the same safety and quality of workmanship.

Fig. 1. Crew Efficiency degradation based on roll Motion (Adapted from Ref. 8.)

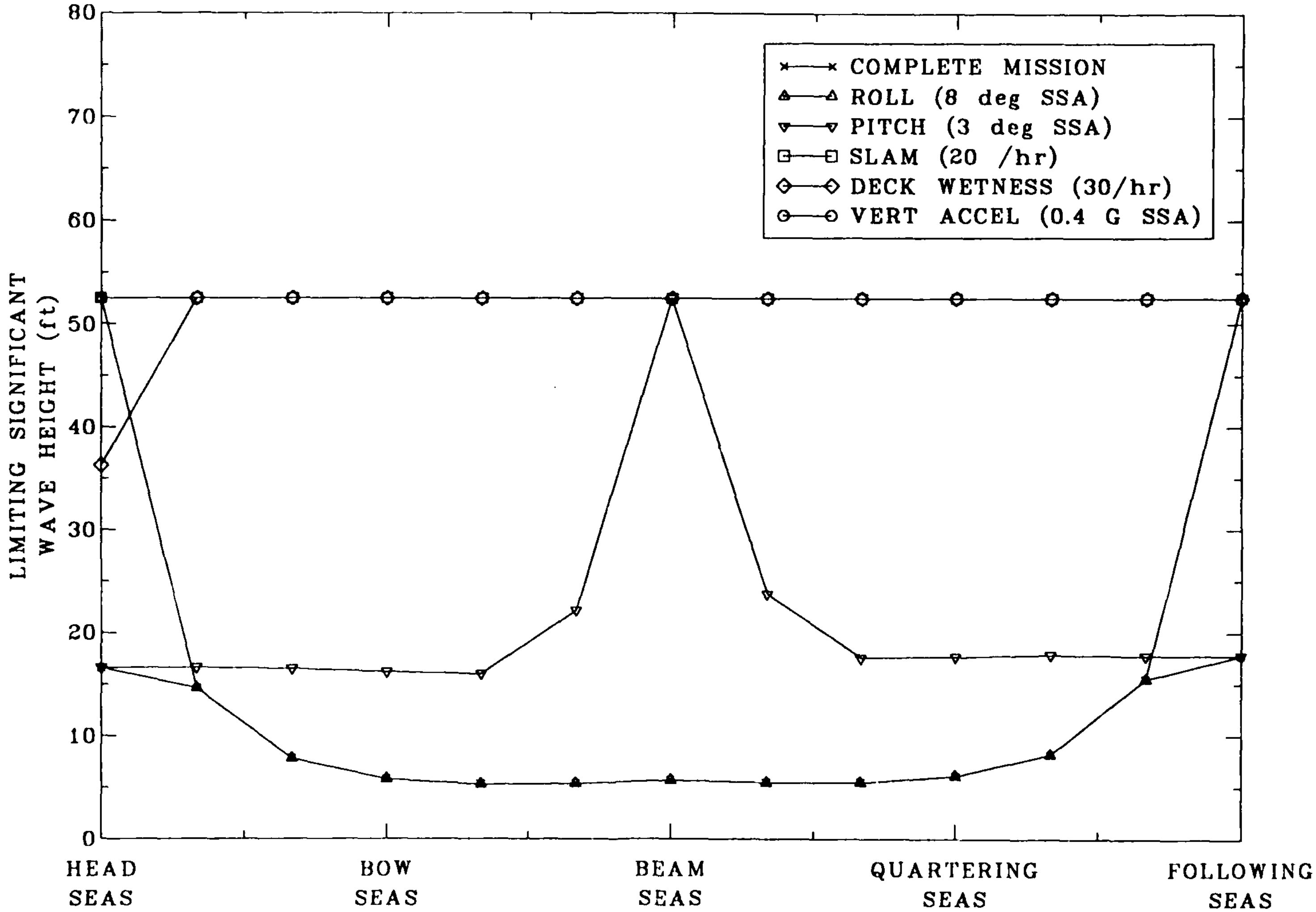


Fig. 2. Limiting wave heights for FFG7 with fins at GIUK gap for various motion criteria. 3.2808 ft = 1 m

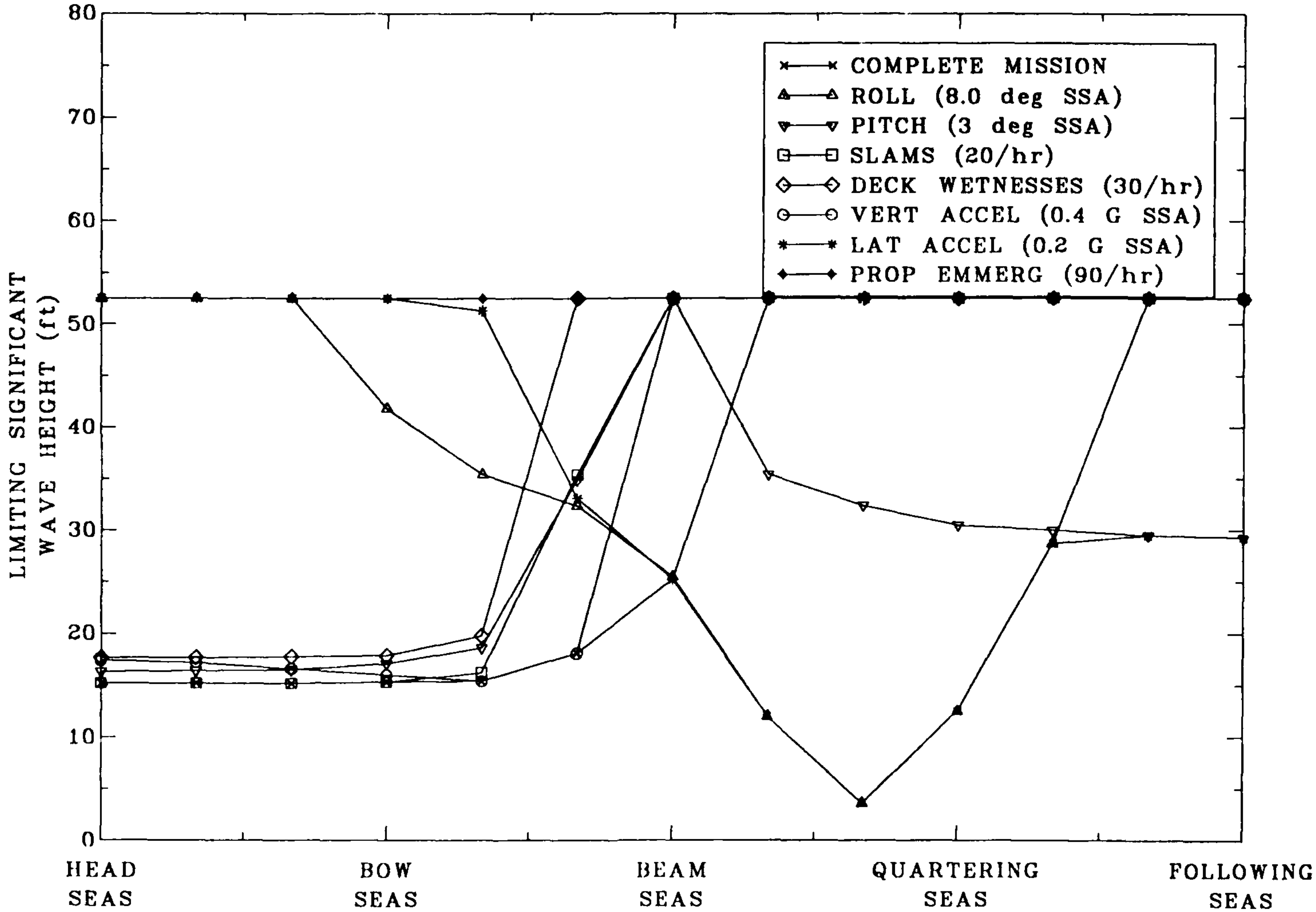


Fig. 3. Limiting wave heights for DD963 at GIUK gap for various motion criteria, at 25 knots. 3.2808 ft = 1 m

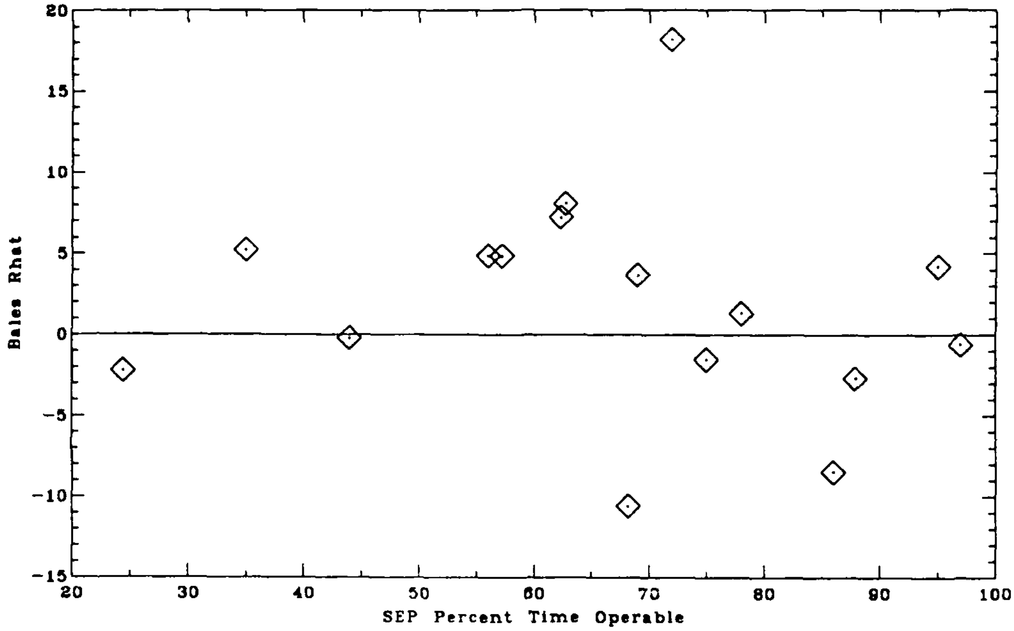


Fig. 4. Comparison of $\hat{R}$ and PTO for representative fleet.

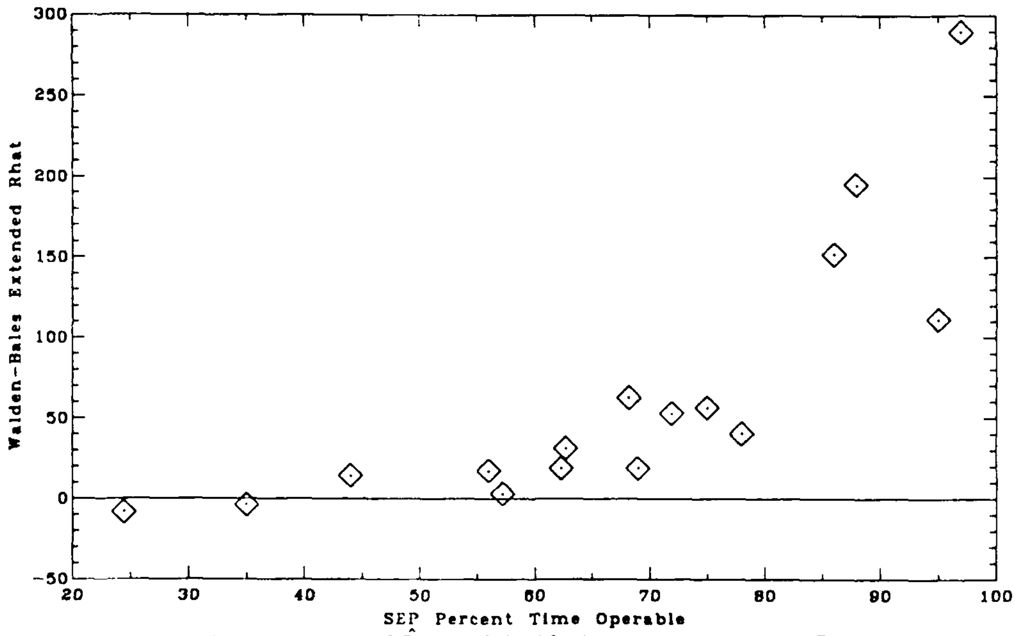


Fig. 5. Comparison of $\hat{R}_\epsilon$ and PTO for representative fleet.

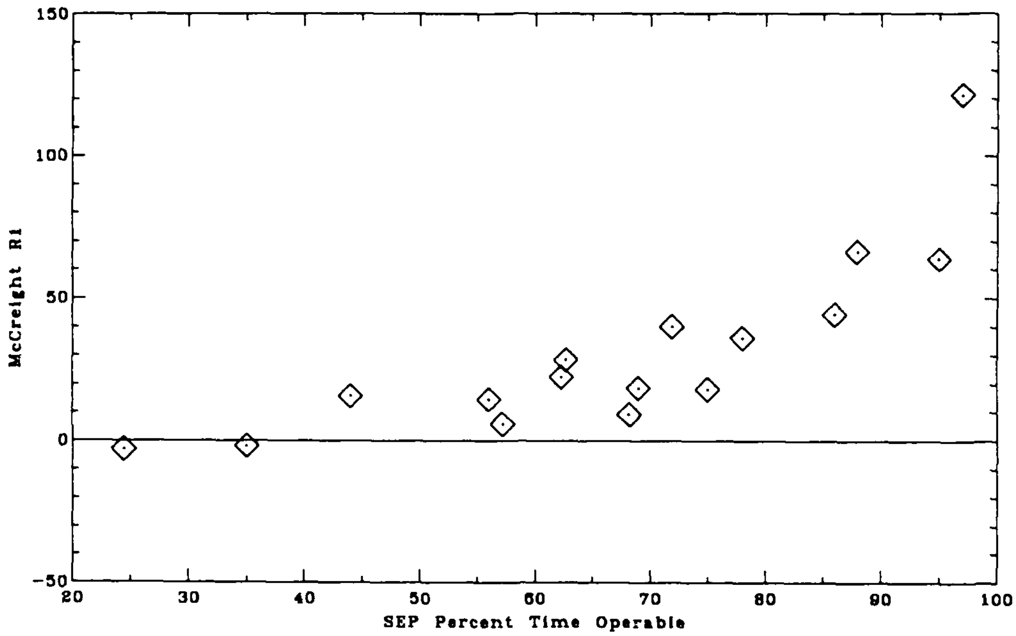


Fig. 6. Comparison of R_1 and PTO for representative fleet.

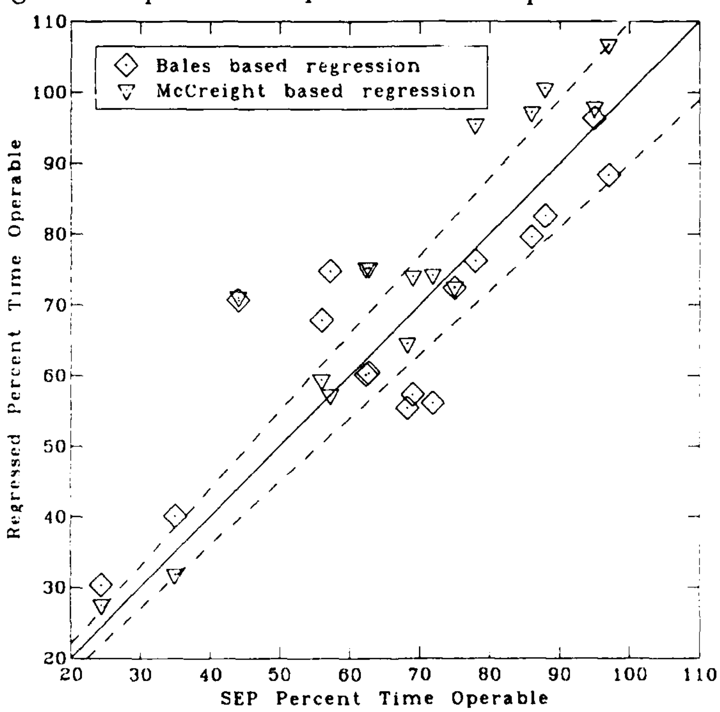


Fig. 7. Regressed PTOs based on Bales and McCreight variables compared with SEP PTO.

Navy Surface Combatant Seakeeping—Transit Mission

• Ship Characteristics

	FFG8 fins	DD963	DDG51	CG47	CGN38	CGN9	BB62	CV41	CVN71
Disp (LT)	3,701	8,195	8,426	9,458	12,031	17,343	57,795	70,279	101,008
Length (ft)	408	529	466	529	560	690	860	900	1,040
Beam (ft)	45	55	59	55	62	71	108	141	134
Draft (ft)	15	20	21	22	23	25	36	35	40

• Percent Time Operable, Winter, Mobility Mission

Giuk Gap[1]	66	71	66	77	71	85	91	92	98
Open N. Atl.[2]	57	62	56	69	63	78	86	88	97

• Percent Time Limited by each Criteria (GIUK Gap)

Roll (8°SSA[3])[4]	19	20	24	12	23	8	4	6	1
Pitch (3°SSA)	13	8	10	7	6	5	2	1	1
Wetness (30/hr)	0	0	0	0	0	0	4	0	0
Slams (20/hr)	0	1	0	1	0	2	0	0	0
Vert. Acc. (.4 G's)	2	1	0	1	0	0	0	0	0
Lat. Acc. (.2 G's)	0	0	0	1	0	0	0	0	0
Prop. Emer. (90/hr)	0	0	0	0	0	0	0	0	0

[1](61°N 15°W) [2](56°N 27°W) [3]Significant Single Amplitude

[4]Limiting value

Conversion: 3.2808 ft = 1 m; 1 LT = 1.015 tonne

Table 1. Winter North Atlantic Ocean surface combatant seakeeping comparison.

Table 2. Winter North Atlantic Ocean amphibious combatant seakeeping comparison.

Navy Amphibious Combatant Seakeeping—Transit Mission

- Ship Characteristics

	LST1179	LSD41	LHD1
Disp (LT)	9,095	15,839	40,042
Length (ft)	500	580	778
Beam (ft)	70	84	106
Draft (ft)	19	20	26

- Percent Time Operable, Winter, Mobility Mission

Giuk Gap[1]	53	81	97
Open N. Atl.[2]	44	72	95

- Percent Time Limited by each Criteria (GIUK Gap)

Roll (8°SSA[3])[4]	39	12	1
Pitch (3°SSA)	5	5	1
Wetness (30/hr)	0	0	0
Slams (20/hr)	0	0	1
Vert. Acc. (.4 G's)	0	0	0
Lat. Acc. (.2 G's)	0	0	0
Prop. Emer. (90/hr)	3	2	0

[1](61°N 15°W) [2](56°N 27°W) [3]Significant Single Amplitude
[4]Limiting value
Conversion: 3.2808 ft= 1 m; 1 LT = 1.015 tonne

Table 3. Winter North Atlantic Ocean auxiliary seakeeping comparison.

Navy Auxiliary Seakeeping—Transit Mission

• Ship Characteristics

	MCM1	TAGOS13	AE36	AO177
Disp (LT)	1,293	2,262	23,630	28,720
Length (ft)	214	204	554	553
Beam (ft)	39	43	90	88
Draft (ft)	12	15	27	34

• Percent Time Operable, Winter, Mobility Mission

	MCM1	TAGOS13	AE36	AO177
Giuk Gap[1]	46	34	82	77
Open N. Atl.[2]	35	24	75	68

• Percent Time Limited by each Criteria (GIUK Gap)

	MCM1	TAGOS13	AE36	AO177
Roll (8°SSA[3])[4]	16	37	11	9
Pitch (3°SSA)	33	30	7	14
Wetness (30/hr)	3	0	0	0
Slams (20/hr)	0	0	0	0
Vert. Acc. (.4 G's)	1	0	0	0
Lat. Acc. (.2 G's)	0	0	0	0
Prop. Emer. (90/hr)	1	0	0	1

[1](61°N 15°W) [2](56°N 27°W) [3]Significant Single Amplitude
[4]Limiting value
Conversion: 3.2808 ft= 1 m; 1 LT = 1.015 tonne

Table 4. Sensitivity study of transit mission for 7 ships at GIUK gap (gp 107, sp 3); longcrested seas.

SHIP	LIMITING CRITERION	TRANSIT MISSION	LIMIT RELAXED 25%				
			ROLL	PITCH	SLAM	WET	PROP
FFG8FINS	Roll	18.6	13.3	19.2	18.6	18.6	18.6
	Pitch	13.4	14.5	4.5	13.6	13.6	13.6
	Slam	0.2	0.2	0.8	* 0.0	0.2	0.2
	Wetness	0.0	0.0	0.0	0.0	0.0	0.0
	Vert. Acc.	2.1	2.1	4.3	2.1	2.1	2.1
	Lat. Acc. *	0.0	0.0	0.0	0.0	0.0	0.0
	Prop Emer.	0.0	0.0	0.0	0.0	0.0	0.0
	Total PTO	65.7	69.9	71.2	65.7	65.7	65.7
TAGOS 13	Roll	36.5	27.3	39.1	36.5	36.5	36.5
	Pitch	30.0	33.9	19.7	30.0	30.0	30.0
	Slam	0.0	0.0	0.0	0.0	0.0	0.0
	Wetness	0.0	0.0	0.0	0.0	0.0	0.0
	Vert. Acc.	0.0	0.0	0.0	0.0	0.0	0.0
	Lat. Acc.	0.0	0.0	0.0	0.0	0.0	0.0
	Prop Emer.	0.0	0.0	0.0	0.0	0.0	0.0
	Total PTO	33.5	38.8	40.9	33.5	33.5	33.5
DD963	Roll	19.9	13.8	20.3	19.9	19.9	19.9
	Pitch	7.6	8.0	1.9	7.7	7.6	7.6
	Slam	0.9	0.9	2.2	0.4	0.9	0.9
	Wetness	0.0	0.0	0.0	0.0	0.0	0.0
	Vert. Acc.	0.9	0.9	1.7	1.3	0.0	0.0
	Lat. Acc. *	0.0	0.0	0.0	0.0	0.0	0.0
	Prop Emer.	0.0	0.0	0.0	0.0	0.0	0.0
	Total PTO	70.7	76.4	73.9	70.7	70.7	70.7
CGN38	Roll	22.8	15.1	23.2	22.8	22.8	22.8
	Pitch	5.8	6.5	0.8	5.8	5.9	5.8
	Slam	0.2	0.2	0.2	0.0	0.2	0.2
	Wetness	0.1	0.1	2.4	0.2	0.0	0.1
	Vert. Acc.	0.0	0.0	0.0	0.0	0.0	0.0
	Lat. Acc.	0.0	0.0	0.0	0.0	0.0	0.0
	Prop Emer.	0.0	0.0	0.0	0.0	0.0	0.0
	Total PTO	71.1	78.1	73.4	71.2	71.1	71.1

NOTE: * indicates a limiting criterion, but less that 0.1%.

Table 4 (Continued.)

SHIP	LIMITING CRITERION	TRANSIT MISSION	LIMIT RELAXED 25% ROLL	PITCH	SLAM	WET	PROP
CV41	Roll	6.3	2.5	6.4	6.3	6.3	6.3
	Pitch	1.3	1.4	0.2	1.3	1.3	1.3
	Slam	0.0	0.0	0.1	0.0	0.0	0.0
	Wetness	0.0	0.0	0.1	0.0	0.0	0.0
	Vert. Acc.	0.0	0.0	0.0	0.0	0.0	0.0
	Lat. Acc.	0.0	0.0	0.0	0.0	0.0	0.0
	Prop Emer.	0.0	0.0	0.0	0.0	0.0	0.0
	Total PTO	92.4	96.1	93.2	92.4	92.4	92.4
LSD41	Roll	12.0	6.1	12.3	12.0	12.0	12.3
	Pitch	5.1	5.4	1.0	5.1	5.1	5.3
	Slam	0.0	0.1	0.5	0.0	0.0	0.1
	Wetness	0.0	0.0	0.0	0.0	0.0	0.0
	Vert. Acc.	0.0	0.0	0.0	0.0	0.0	* 0.0
	Lat. Acc.	0.0	0.0	0.0	0.0	0.0	0.0
	Prop Emer.	2.3	2.6	3.2	2.3	2.3	1.2
	Total PTO	80.6	85.8	83.0	80.6	80.6	81.1
AO177	Roll	9.1	5.4	9.6	9.1	9.1	9.1
	Pitch	13.7	14.1	5.2	13.7	13.7	14.1
	Slam	0.0	0.0	0.0	0.0	0.0	0.0
	Wetness	0.0	0.0	0.2	0.0	0.0	0.0
	Vert. Acc.	0.0	0.0	0.0	0.0	0.0	0.0
	Lat. Acc.	0.0	0.0	0.0	0.0	0.0	0.0
	Prop Emer.	0.6	0.6	2.3	0.6	0.6	0.1
	Total PTO	76.6	79.9	82.7	76.6	76.6	76.7

NOTE: * indicates a limiting criterion, but less that 0.1%.

Table 5. Sensitivity study of transit mission for 7 ships at open ocean N. Atlantic (gp 149, sp 3); longcrested seas.

SHIP	LIMITING CRITERION	TRANSIT MISSION	LIMIT RELAXED 25% ROLL	PITCH	SLAM	WET	PROP
FFG8FINS	Roll	21.8	15.9	22.9	21.8	21.8	21.8
	Pitch	18.4	19.9	7.1	18.4	18.4	18.4
	Slam	0.2	0.2	0.9	* 0.0	0.2	0.2
	Wetness	0.0	0.1	0.0	0.0	0.0	0.0
	Vert. Acc.	2.4	2.4	5.4	2.4	2.4	2.4
	Lat. Acc. *	0.0	0.0	0.0	0.0	0.0	0.0
	Prop Emer.	0.0	0.0	0.0	0.0	0.0	0.0
	Total PTO	57.2	61.6	63.7	57.2	57.2	57.2
TAGOS 13	Roll	41.4	31.9	45.0	41.4	41.4	41.4
	Pitch	34.2	39.0	23.9	34.2	34.2	34.2
	Slam	0.0	0.0	0.0	0.0	0.0	0.0
	Wetness	0.0	0.0	0.0	0.0	0.0	0.0
	Vert. Acc.	0.0	0.0	0.0	0.0	0.0	0.0
	Lat. Acc.	0.0	0.0	0.0	0.0	0.0	0.0
	Prop Emer.	0.0	0.0	0.0	0.0	0.0	0.0
	Total PTO	24.4	29.1	31.1	24.4	24.4	24.4
DD963	Roll	24.3	17.8	25.0	24.3	24.3	24.3
	Pitch	11.2	12.0	3.1	11.3	11.2	11.2
	Slam	0.9	0.9	2.9	0.4	0.9	0.9
	Wetness	0.0	0.0	0.0	0.0	0.0	0.0
	Vert. Acc.	1.2	1.2	2.5	1.6	1.2	1.2
	Lat. Acc. *	0.0	0.0	0.0	0.0	0.0	0.0
	Prop Emer.	0.0	0.0	0.0	0.0	0.0	0.0
	Total PTO	62.3	68.1	66.5	62.4	62.3	62.3
CGN38	Roll	28.0	19.1	28.8	28.0	28.0	28.0
	Pitch	9.0	10.1	1.4	9.0	9.0	9.0
	Slam	0.2	0.2	0.2	0.0	0.2	0.2
	Wetness	0.1	0.1	3.6	0.3	0.0	0.1
	Vert. Acc.	0.0	0.0	0.0	0.0	0.0	0.0
	Lat. Acc.	0.0	0.0	0.0	0.0	0.0	0.0
	Prop Emer.	0.0	0.0	0.0	0.0	0.0	0.0
	Total PTO	62.7	69.8	66.1	62.7	62.7	62.7

NOTE: * indicates a limiting criterion, but less that 0.1%.

Table 5 (Continued.)

SHIP	LIMITING CRITERION	TRANSIT MISSION	LIMIT RELAXED 25%				
			ROLL	PITCH	SLAM	WET	PROP
CV41	Roll	9.8	4.2	10.0	9.8	9.8	9.8
	Pitch	2.3	2.5	0.3	2.3	2.3	2.3
	Slam	0.0	0.0	0.1	0.0	0.0	0.0
	Wetness	0.0	0.0	0.2	0.0	0.0	0.0
	Vert. Acc.	0.0	0.0	0.0	0.0	0.0	0.0
	Lat. Acc.	0.0	0.0	0.0	0.0	0.0	0.0
	Prop Emer.	0.0	0.0	0.0	0.0	0.0	0.0
	Total PTO	87.9	93.3	89.4	87.9	87.9	87.9
LSD41	Roll	16.8	9.8	17.2	16.8	16.8	16.9
	Pitch	8.3	8.9	1.8	8.4	8.3	8.7
	Slam	0.0	0.1	0.8	0.0	0.0	0.1
	Wetness	0.0	0.0	0.0	0.0	0.0	0.0
	Vert. Acc.	0.0	0.0	0.0	0.0	0.0	* 0.0
	Lat. Acc.	0.0	0.0	0.0	0.0	0.0	0.0
	Prop Emer.	2.8	3.3	4.5	2.8	2.8	1.5
	Total PTO	71.9	77.8	75.6	71.9	71.9	72.8
AO177	Roll	12.2	7.9	13.0	12.2	12.2	12.3
	Pitch	18.9	19.6	8.3	18.9	18.9	19.4
	Slam	0.0	0.0	0.0	0.0	0.0	0.0
	Wetness	0.0	0.0	0.3	0.0	0.0	0.0
	Vert. Acc.	0.0	0.0	0.0	0.0	0.0	0.0
	Lat. Acc.	0.0	0.0	0.0	0.0	0.0	0.0
	Prop Emer.	0.7	0.7	3.1	0.7	0.7	0.0
	Total PTO	68.2	71.8	75.3	68.2	68.2	68.3

NOTE: * indicates a limiting criterion, but less that 0.1%.

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